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Award #: DE-EE0008001

Integration of a DER Management System in Riverside

Lead PI: Prof. Hamed Mohsenian-Rad

Project Team: UCR, SGS, LBNL, RPU, PG&E, GridBright, LLNL.

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Project Overview and Components

- **Objective**: Development, validation, and field demonstration of a DER Management System (DERMS) with advanced sensor data and a novel adaptive control algorithm to enhance visibility and controllability of DERs in power distribution system.

- **Components**:
  - Platform Development
  - Algorithm Development
    - Monitoring and Control
  - Hardware-in-the-Loop Testing
  - Pilot Demonstration in Riverside, CA
  - Cost Benefit Analysis and Commercialization Plan Development

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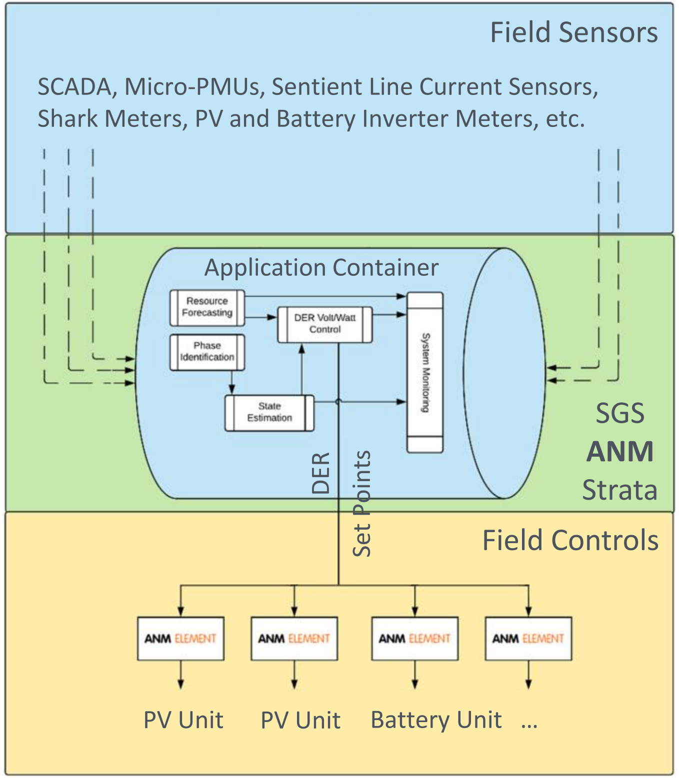
Developed DERMS Platform

Hierarchical "DERMS + App" Architecture
(Suitable for Smaller or Public Utilities)



HIL Testing

Field Demonstration

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Developed DERMS Platform

- **Advanced Monitoring based on Heterogeneous Measurements**: The monitoring algorithms in this project utilize a heterogeneous set of *legacy* and *advanced* sensor data, ranging from behind-the-meter DER sensors, both PVs and batteries, distribution-level PMUs, substation SCADA systems, and line current sensors, with their *limited availability*; in order to infer practical network conditions that otherwise would have to be computed from an often inaccurate models.

- **Advanced Model-Free, Layered, and Clustered DER Control**: The DER control algorithms use the concept of *Extremum Seeking* (ES), which is a *model-free* probing-based control method. To the best of our knowledge, this was the first time ES method is being tested on major real-world inverters; both *individually* and in a *cluster*. The algorithm has been customized for the needs in this project.

  It was shown that even legacy equipment (when paired with a few additional advanced equipment) can support such advanced control.

Developed DERMS Platform

- **Flexible Technology**: The solution that is developed and demonstrated in this project is modular and flexible; and is based on the "*DERMS+App*" paradigm; it will be transformational to utilities, including the smaller municipal utilities, which may not have the resources to deploy advanced distribution system and DERMS solutions in order to support high penetration of solar power integration..

  This flexible DERMS framework that resembles an "operating system", i.e., the ANM framework, can host a range of algorithms that are developed on *different platforms* (e.g., MATLAB and Python) and interact with *different hardware devices* (e.g., different PV and battery inverters, new and old, different types of sensors).

  Utilities can *customize* their solution based on their needs and budget.

UNIVERSITY OF CALIFORNIA RIVERSIDE

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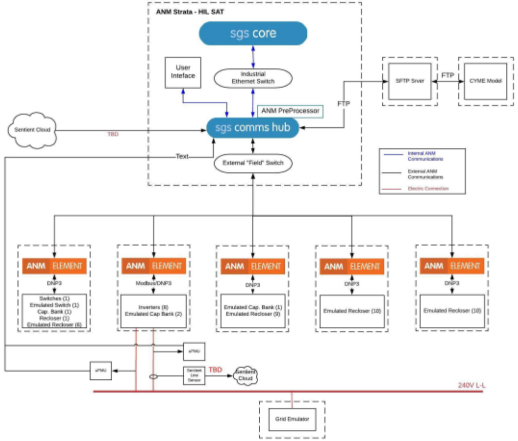
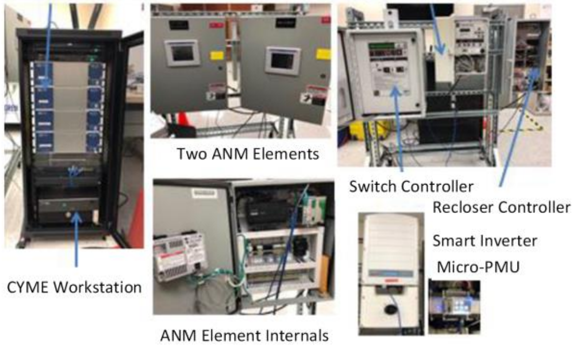
HIL Testing - Overview

- Purpose of HIL Testing: *provide a laboratory environment that will test the response of physical hardware, communication system, and overall performance of the DER management system*
- Communications was done using DNP3 over TCP/IP
- ANM Strata operated across several IT components
  - Beaglebones Black used to emulate 3 ANM Elements
- Circuit emulation was done using the CYME models of the RPU Power Distribution Feeders 1224 and 1225
  - CYME model was developed by converting Synergi model
- Hardware:
  - ANM Elements
  - Eight PV inverters
  - S&C 5801 Switch Controller
  - IntelliCAP Capacitor Bank
  - Two PSL Micro-PMUs
  - Sentient Line Current Sensor
  - Raspberry PI to emulate switch, capacitor, breaker controllers
  - Total Physical Node Count: 105.



Architecture



Hardware

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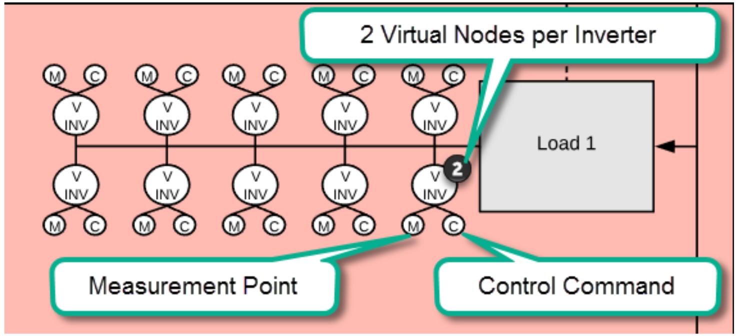
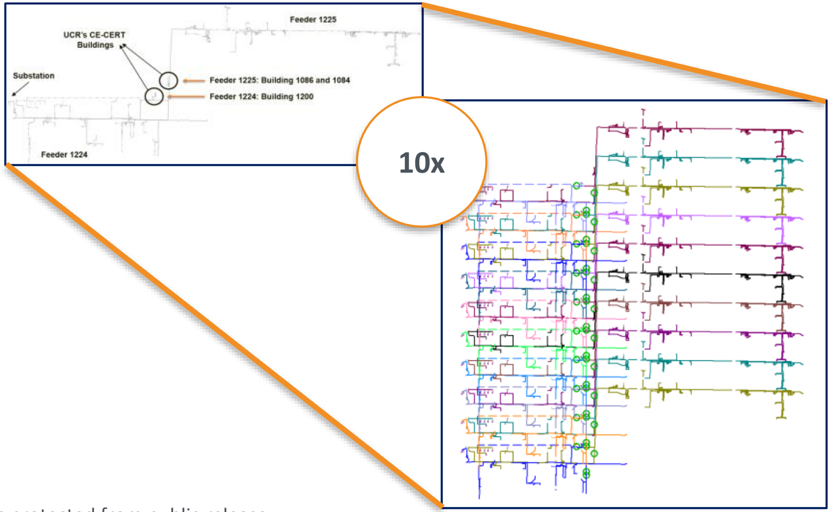
HIL Testing – Scaling Up

- Scaling up to 10,000 nodes:
    - It was achieved by expanding the existing setup to 1000 Nodes and then multiplying the setup 10 times.
- Expansion/scaling was achieved using virtual nodes
- A virtual node is either a sensor point or a control point.
    - A PV virtual inverter is both senor and control points
- Within the base circuit model there are 55 loads
    - Each load was given either 5 or 10 virtual PV inverter elements (based on size) to achieve 1000 Nodes
- Scaling AMN Strata required scripting and automation to streamline the manual process
    - Docker was used to create 1000 DNP channels
    - Mapping of the application points was automated using C# scripts.





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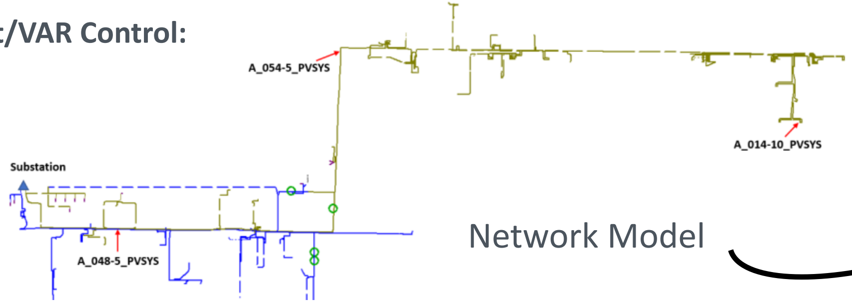
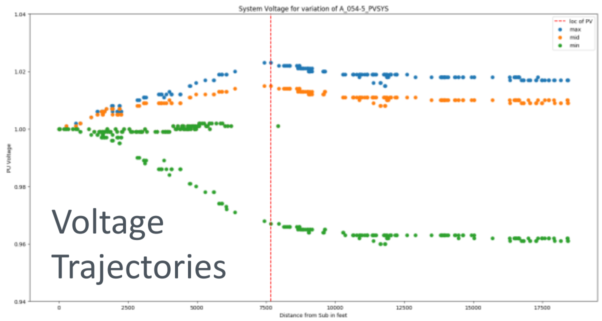
HIL Testing – Sample Results

- Selected use cases were tested on HIL testing platform:

Volt/VAR Control:



Network Model



Distribution System State Estimation:

- Heterogeneous measurements are used: Micro-PMUs, line sensors, SCADA, pseudo-measurements, etc.
- Different Scenarios:
  - load level, PV generation, capacitor bank switching.

Topology Reconfiguration:

- Different Scenarios: varying PV weather and load profiles
- Each scenario takes around 188 seconds (3’08”) to run.
- Binary output files showed the results.

The platform, communications, and all applications ran successfully.

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Field Demonstration

Field Demonstration

- Three Substations and 10 Feeders
- All applications were tested on Feeder 1224.
- At least one application is tested on every other Feeder.

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Highlight of Monitoring Algorithms

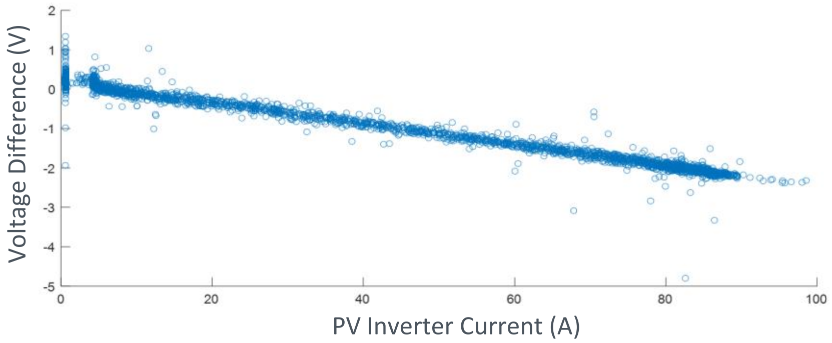
Distribution System State Estimation (DSSE)

- Utilizing Heterogeneous Measurements: SCADA, Micro-PMUs, Switches Status, Sentient Line Current Sensors (non-contact), DER Inverter Sensors.

- First Time Such Application
- Challenging Formulation

- Compensate for Missing Data
- Impact of Load Transformer Turn Ratio

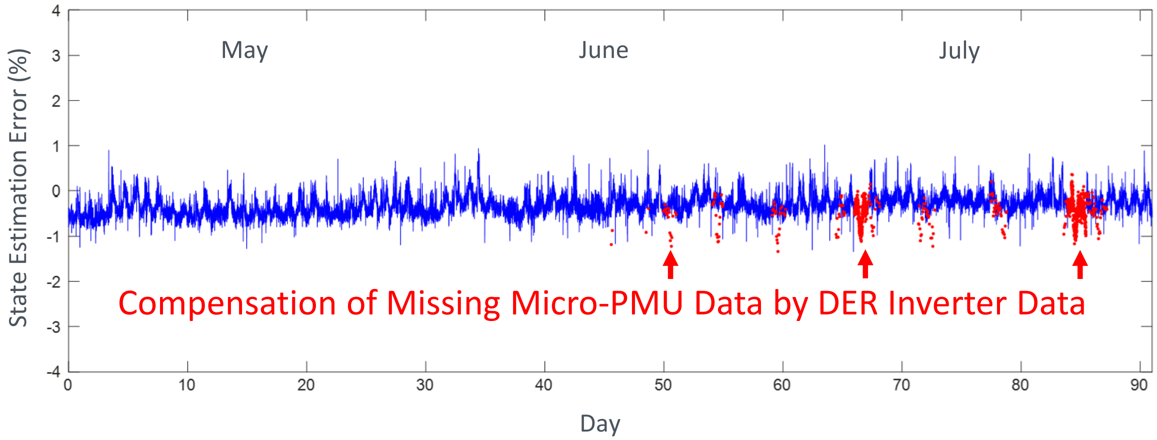
(Regression Model)



Highlight of Monitoring Algorithms

Distribution System State Estimation (DSSE)

- Utilizing Heterogeneous Measurements: SCADA, Micro-PMUs, Switches Status, Sentient Line Current Sensors (non-contact), DER Inverter Sensors.



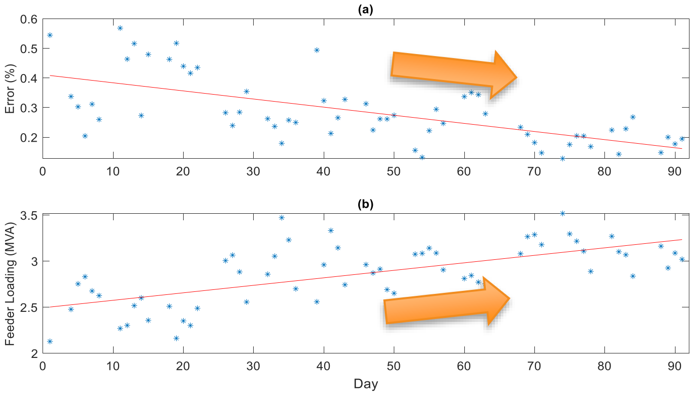
Highlight of Monitoring Algorithms

Distribution System State Estimation (DSSE)

- Accuracy of Utility Models and Sensitivity Analysis:

	Average of Error in DSSE			
Month	All Day	Weekday		Weekend
		Day	Night	
May	0.46	0.38	0.47	0.53
June	0.35	0.26	0.36	0.45
July	0.27	0.25	0.30	0.32

Utility Models Better Fit
High Loading Conditions



Early COVID-19 Shut Down

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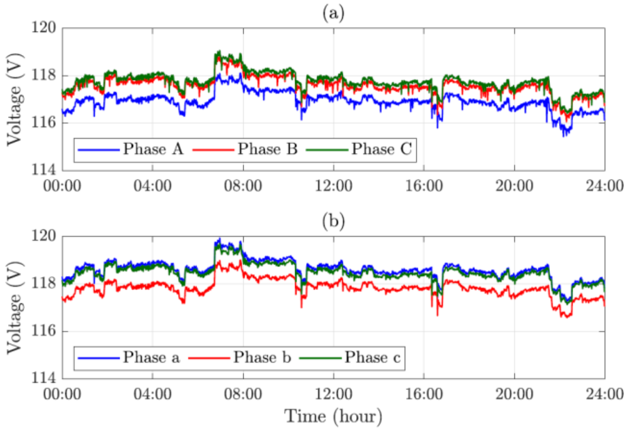
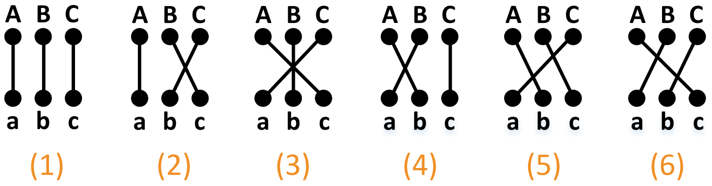
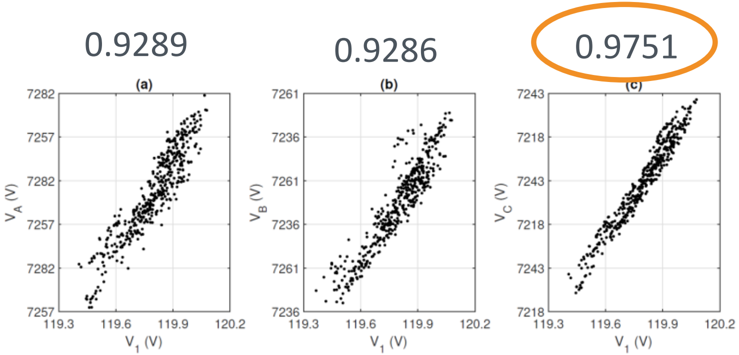
Highlight of Monitoring Algorithms

Phase Identification (PI)



$$\underset{i,j,k\in\{a,b,c\}}{\operatorname{argmax}} \ \frac{1}{3}\Big\{\rho\big(v_A(t),v_i(t)\big)+\rho\big(v_B(t),v_j(t)\big)+\rho\big(v_C(t),v_k(t)\big)\Big\}$$





Correlation-Based Methods *Sometimes* Work Fine.

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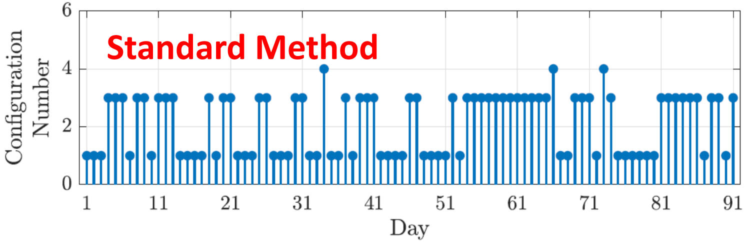
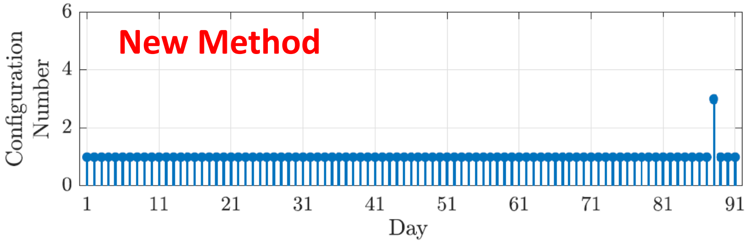
Highlight of Monitoring Algorithms

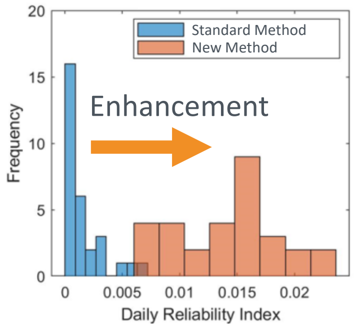
Phase Identification (PI)

- New Method based on Reliability Assessment.





High-level Idea: Break down the day into several smaller time slots. Use two data-driven *Reliability Criteria* to select only the *most reliable chunks of data* on each day to solve the phase identification problem.



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Highlight of Monitoring Algorithms

Resource Forecasting (RF)

- Different deep neural network models were examined: Recurrent Neural Network (RNN), Long Short-Term Memory (LSTM), and Gated Recurrent Unit (GRU).

  → Worked best on various PV units.

- Challenge: Some PV units were installed recently (*limited historical data*).

Proxy Method

Historical Data - **Old** PV Unit → RF Models

Historical Data - **New** PV Unit → RF Models

Accuracy (%nRMSE)

New PV Sites	LSTM *without* Proxy	LSTM *with* Proxy
Lot 30	17.67%	12.55%
Lot 32	15.80%	11.04%

Proxy Site: 2 Miles Away (Different Feeders)

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Highlight of Monitoring Algorithms

Resource Forecasting (RF)

- Different deep neural network models were examined: Recurrent Neural Network (RNN), Long Short-Term Memory (LSTM), and Gated Recurrent Unit (GRU).

- Another Challenge: Unusual change in weather conditions (example: a highly cloudy day after a series of mostly sunny days).

→ **Use Satellite Data for Weather and Irradiance Forecast** (API from solcast)

- Global Horizontal Irradiance
- Cloud Level
- Temperature

Method	Accuracy (% of nRMSE < 30%)
Without API	97.6%
With API	100%

PV Site: Building 1200 (average nRMSE = 12.47%)

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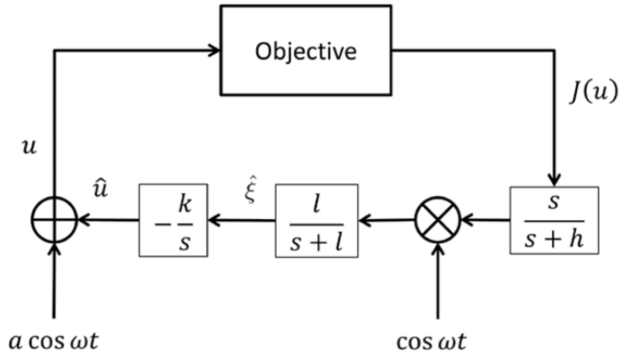
Highlight of Control Algorithms

- Voltage management accomplished through **Extremum Seeking (ES) Control**
- Advantages:
  - Model-free, input-output based approach
  - Very communication light
  - Scalable distributed optimal control
  - Minimize any convex objective
  - Controllers can be objective agnostic
- The ES Control Process:
  - ESC resource perturbs its output (P and/or Q) with a sinusoidal signal
  - A central entity composes an objective off system measurements
  - Objective is broadcast to all ESC resources
  - DERs independently identify their gradient on the objective and perform gradient descent

Voltage Control Approach

- Each ES Controller includes:
  - A high-pass filter
  - Demodulation
  - Low-pass filter
  - An integrator
  - Addition of the probing sinusoid



- The ES Control Considerations:
  - The speed of convergence is related to the frequency of the probing signal.
  - The neighborhood of the optimal objective is also influenced by both the probe frequency and amplitude, as well as the integrator gain.

- In field testing, the inverter hardware available for demonstration limited probing frequency and forced management through purely real power.

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Voltage Control – Selected Results

- Demonstrations performed on 3 PV units and 1 Battery trailer connected to two RPU feeders (1224 and 1225) under Hunter substation.
- Objective was to drive voltages measured at the inverter or at the building towards a target value (the set point).
- 13 tests performed from January to July.
  - 4-6 hours long
  - Voltage targets between 284 and 290V L-N
  - 11 tests on individual DER control; 2 tests on coordinated DER cluster control.
  - 3 tests performed with battery system mimicking PV output
- 3 Tests are selected here to highlight the voltage control results.

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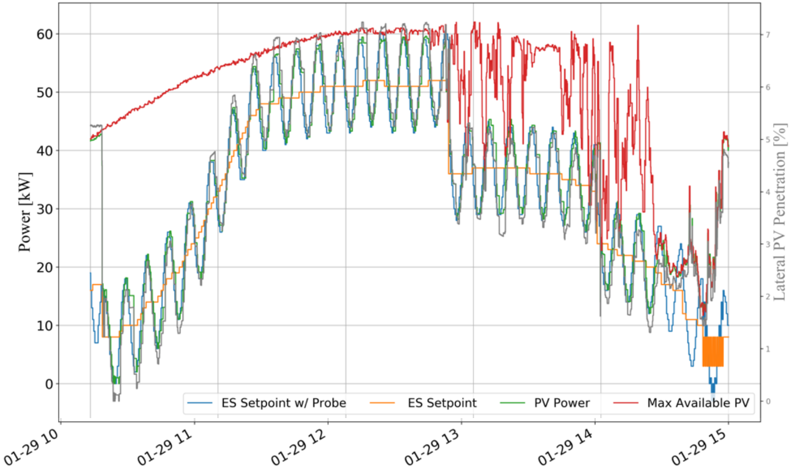
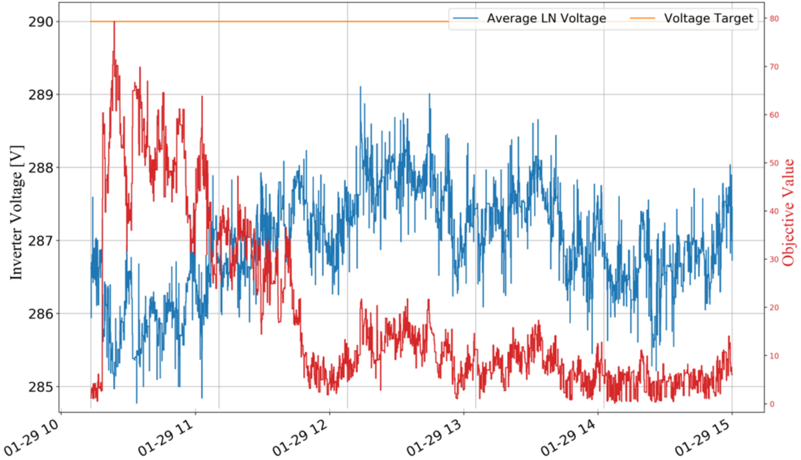
Voltage Control – Selected Results

- Test #3: January 29th, PV Inverter connected to Feeder 1224
  - Inverter Voltage Target: 290V L-N





- ESC drives the system toward maximum power
- Curtails to ensure probing during cloudy weather

- As power increases, so does local voltage
- Correspondingly, the value of the objective is driven toward zero (i.e., the goal of the gradient-descent).

Voltage Control – Selected Results

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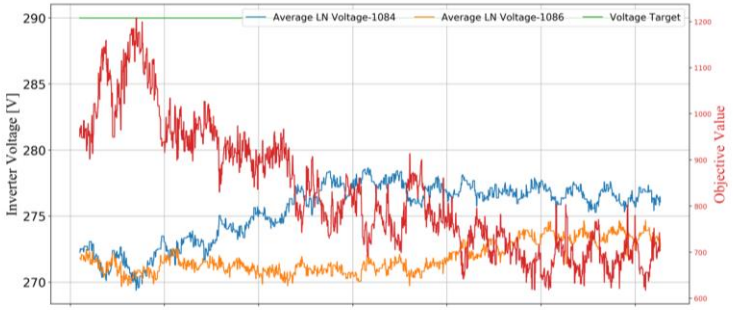
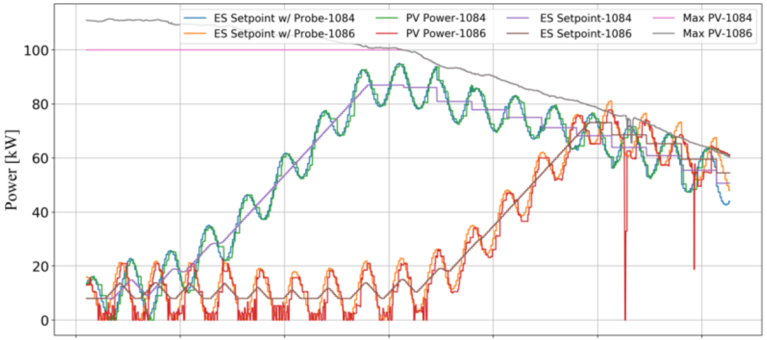
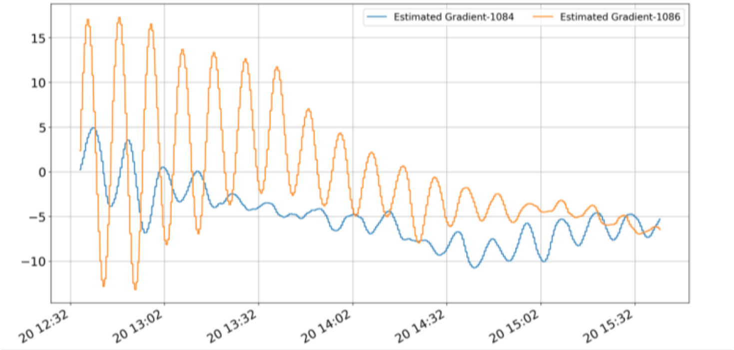
- Test #4 (DER Cluster), February 20th, 2 PV inverters on Feeder 1225
  - Both inverter voltage target of 290V
  - PV at Bldg 1084 probes at 0.001515 Hz
  - PV at Bldg 1086 probes at 0.00167 Hz



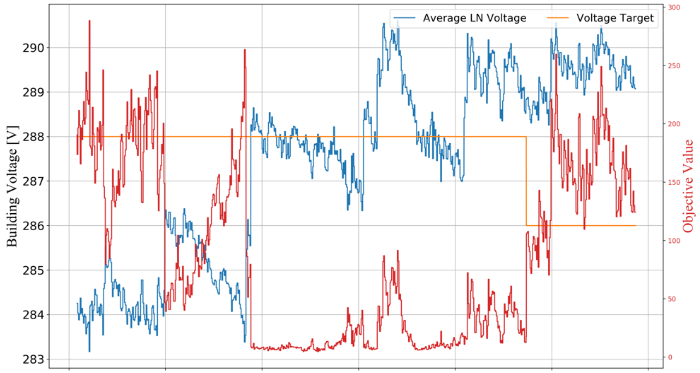
- PV 1084 is first to estimate correct negative, and so drives toward saturation first.

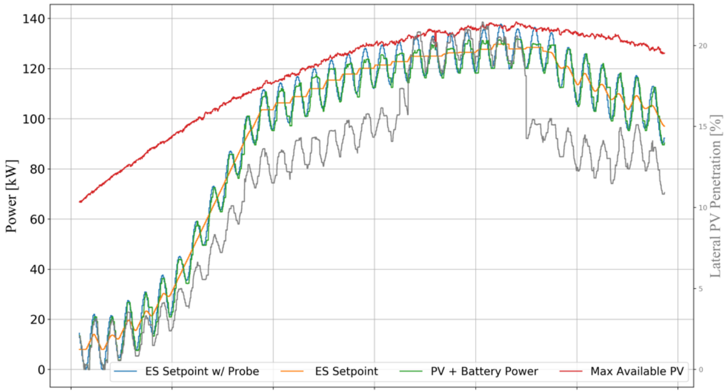


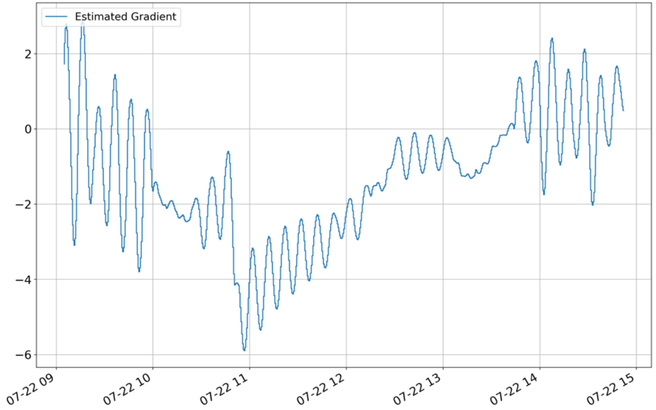


Voltage Control – Selected Results

- Test #12 (Different DERs), July 22nd, PV + Battery on Feeder 1224
  - Building Voltage Target Changes from 288 to 286 V L-N
  - Estimated gradient flips sign and system begins curtailing as desired.







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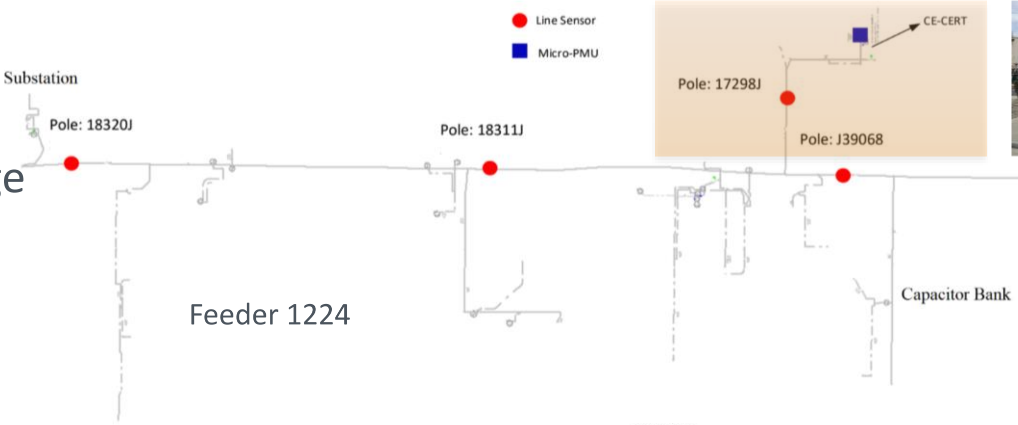
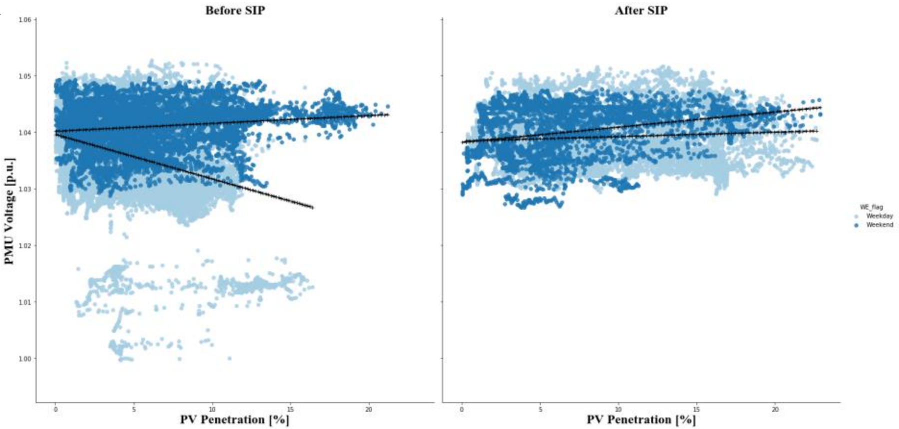
High PV Penetration – Voltage Analysis

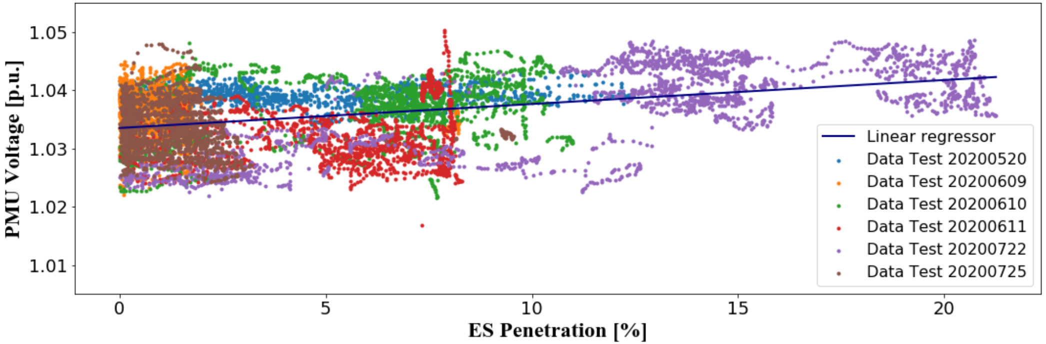
- Analyzing load in the shaded region of Feeder 1224 for voltage
  - Current sensor placed at pole 17298J
  - Micro-PMU on low-side of CE-CERT Xfmr

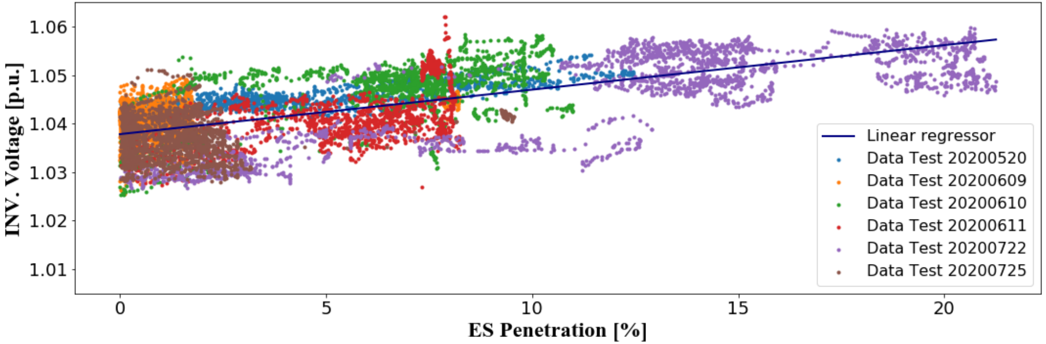


- Voltage Sensitivity to uncontrolled inverter output before and after shelter in place.
  - Regression is negative for weekdays before SIP
  - PV Penetration means ratio of PV output to lateral loading.



High PV Penetration – Voltage Analysis





Regression Coeff.	PV Power [kW]	PV Penetration [%]
μPMU Voltage [p.u.]	0.000047892	0.0003984
Inverter Voltage [p.u.]	0.00013098	0.0009652

- Regression has positive slope when controlling the output of the inverters.
- Due to control, inverter output and the lateral load shape are not tightly correlated.
- If linear to high PV penetration – PV generation at 50% of load will only increase by 0.02 p.u at the bldg μPMU.

* Operational PV Penetration presented

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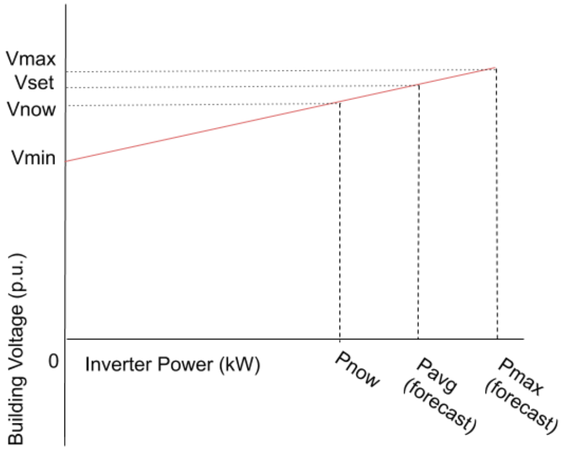
Voltage Setpoint Selection

- A method to select voltage setpoints based on the RF and DSSE algorithms (i.e, current and forecasted network conditions) was developed.
- Algorithmic approach:
    - Historical and forecasted state information was clustered via k-means into 6 state space regions.
    - For each state space region, a regression was performed to determine voltage sensitivity to real-power injection
    - Given a current state, and future forecast, the cluster for current conditions is used to determine the proper sensitivity to apply.
    - Voltage targets were determined as the forecasted midpoint of the range that voltage could take given conditions and PV power.



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Voltage Control – Lessons Learned

- Extremum Seeking Control can successfully operate inverter real power to counter voltage excursions, even with slow inverter response characteristics
- In one test, under low load conditions, ES Control could not find its gradient during the test and was unable to operate. More work examining system conditions for failure and contingency scenarios can be done in the future.
- In the conditions on project feeders, high penetrations of PV was possible, though volt-watt control provided limited voltage sensitivity. Future work with VAR capable control would be valuable to achieve more controllability.

Cost Benefit Analysis – Overview

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- Benefits: Broken down based on the four algorithms in field demonstration.
  - Volt/Watt Control, Resource Forecasting, State Estimation, Phase Identification.

- Cost Categories:
  - Equipment and Software Costs
  - Equipment Installation Costs
  - Maintenance and Operational Costs

- Benefit to Cost Ratio:

$$\frac{\$11{,}140{,}245}{\$9{,}956{,}055} = 1.12$$

Capacity	Name/Address	Year in Operation	Number of ANM Elements
0.46 MW	UC Riverside CE-CERT	2016	2
4.32 MW	UC Riverside Lot 30 & 32	2017	1
3.2 MW	UC Riverside Solar Tracking	2015	1
7.3 MW	Tequesquite Landfill Project	2015	1
0.808 MW	1299 Galleria at Tyler	2017	1
0.772 MW	6659 Sycamore Canyon Blvd	2018	1
0.59 MW	1100 Citrus St MSA1	2015	1
0.53 MW	1101 Citrus St MSA2	2015	1
0.528 MW	3520 Tyler St on 6/22/2018	2018	1
0.508 MW	6676 Lance Dr	2019	1
0.473 MW	6250 Valley Springs Pw	2019	1
0.408 MW	2755 Canyon Springs Pkwy	2017	1
0.407 MW	3536 Adams St	2019	1
0.359 MW	6125 Sycamore Canyon Blvd	2011	1
0.272 MW	3600 Galleria @ Tyler GU	2016	1
0.251 MW	6900 Jurupa Ave	2019	1
0.232 MW	3080 12th St	2014	1
0.219 MW	6446 Fremont St	2019	1
0.203 MW	6446 Fremont St	2019	1
21.840 MW	Total		20

PV Installations over 200 kW on RPU Service Territory

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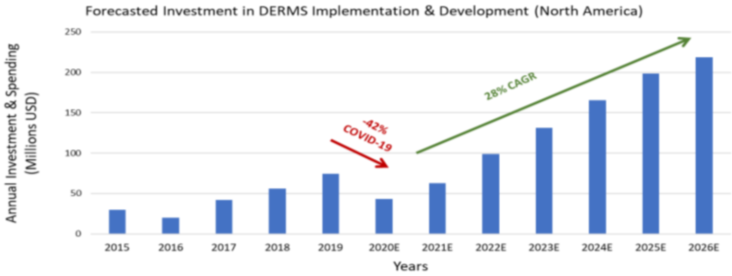
Market Place Overview

- Three predominant variations of DERMS solutions in the market today:
  1. Enterprise DRMS ‘Evolutions’
     - Products that evolved out of ‘Demand Response Management Systems’ (DRMS) enterprise.
  2. Enterprise ADMS ‘Extensions’
     - Products that extend ‘Advanced Distribution Management Systems’ (ADMS) enterprise.
  3. Standalone DERMS Solutions
     - Mostly startups that merge selected DRMS and ADMS functions into new solution focused on DERs.

- Market Readiness:
  - Penetration rates have not hit a critical mass to cause enough grid problems.
  - Non-wires alternative ‘incentive’ programs have not been designed and approved.
  - Externalities like cheap natural gas, COVID, and shifting FERC/political priorities.



Caution: These estimates are based on optimistic industry analysis.

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Go-to-Market Strategy

Some features of the DERMS Solution in this project:

1. Measurement based control
2. Layered, clustered control
3. Larger resource clusters
4. Integration of legacy network equipment controls
5. Extensible algorithms
6. Support a variety of hardware device types

- Market Segments
  - Traditional market is Distribution Utilities. Some ISO/RTO/TSOs also need 'DERMS'.
  - Potentially larger emerging market includes microgrid owner/operators, energy traders, retailers, developers, demand aggregators, and DER asset developers.
- Market Approach, Pricing Strategy, Price Formation, etc.
  - Difficult to price 'algorithms' a la carte because of 'value stacking'
  - Packaged within SGS platform; or released as open source or licensed, etc.
  - Value-add or incremental module, Freemium and/or subscription pricing, etc.

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Commercialization Recommendations

- The incremental business value and cost impact of individual DER algorithms is relatively small in the typical evaluation of a new ADMS, DERMS, or Planning solution, which is how utilities and others generally acquire software.
- Most utilities have little practical use for standalone algorithms since it will ultimately need to be integrated within their operational processes and systems anyway.
- The best tech-to-market path for innovative new DER related algorithms is to have vendors like SGS (or other vendors) sponsor and pay for to commercialize the developed algorithms within their existing products and sell them as part of an overall solution package.
- Due to the nature of the current immature DERMS market (consisting of multiple different product types for multiple non-overlapping market segments), other vendors and licensing schemes could also be considered in the future to maximize value through completely different channels, so long as those vendors are mostly non-competitive with SGS.

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Publications

[1] J. MacDonald, M. Baudette, K. Dunn, and H. Mohsenian-Rad, “Field Demonstration of Inverter-based Voltage Management using Extremum Seeking Control,” in *Proc. of IEEE Power and Energy Society (PES) General Meeting*, Washington, DC, 2021.

[2] M. Izadi and H. Mohsenian-Rad, “Improving real-world measurement-based phase identification in power distribution feeders with a novel reliability criteria assessment,” submitted to the *IEEE PES Innovative Smart Grid Technologies Europe*, Espoo, Finland, 2021.

[3] P. Khaledian, A. Aligholian and H. Mohsenian-Rad, “Event-Based Analysis of Solar Power Distribution Feeder Using Micro-PMU Measurements,” in *Proc. of IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, Washington, DC, 2021.

[4] M. Sankur, M. Baudette, J. Macdonald, and D. Arnold, “Batch measurement extremum seeking control of distributed energy resources to account for communication delays and information loss,” in *Proc. of the HICSS*, Maui, HI, 2020.

[5] M. Farajollahi, A. Shahsavari and H. Mohsenian-Rad, “Topology Identification in Distribution Systems Using Line Current Sensors: An MILP Approach,” *IEEE Transactions on Smart Grid*, vol. 11, no. 2, pp. 1159-1170, Mar. 2020.

[6] M. Farajollahi, A. Shahsavari and H. Mohsenian-Rad, “Linear distribution system state estimation using synchrophasor data and pseudo-measurement,” in Proc. of IEEE Conf. on Smart Grid Synchronized Measurements & Analytics (SGSMA), College Station, TX, 2019.

[7] A. Shahsavari, M. Farajollahi, E. M. Stewart, E. Cortez and H. Mohsenian-Rad, “Situational Awareness in Distribution Grid Using Micro-PMU Data: A Machine Learning Approach,” *IEEE Trans. on Smart Grid*, vol. 10, no. 6, pp. 6167-6177, Nov. 2019.

[8] A. Shahsavari, M. Farajollahi and H. Mohsenian-Rad, “Individual Load Model Parameter Estimation in Distribution Systems Using Load Switching Events,” *IEEE Transactions on Power Systems*, vol. 34, no. 6, pp. 4652-4664, Nov. 2019.

[9] M. Farajollahi, A. Shahsavari, E. M. Stewart and H. Mohsenian-Rad, “Locating the Source of Events in Power Distribution Systems Using Micro-PMU Data,” *IEEE Transactions on Power Systems*, vol. 33, no. 6, pp. 6343-6354, Nov. 2018.

[10] A. Shahsavari, M. Farajollahi, E. Stewart, C. Roberts, F. Megala, L. Alvarez, E. Cortez, H. Mohsenian-Rad, “Autopsy on active distribution networks: a data-driven fault analysis using micro-PMU data,” in *Proc. of IEEE PES NAPS*, Morgantown, WV, 2017.

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Thank You

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